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Progress is summarized on the mechanical and shielding systems for a 1 GeV Linac and Storage Ring to drive an UV/XUV Free Electron Laser. Progress is summarized on injector redesign and undulator design. Training and coupling activities are summarized.

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Report F-AFOSR-88-0238

# Research on Advanced Source Development and Applications

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3 August 1990

Final Report for Period 1 July 1988 - 31 October 1989

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Final Report, AFOSR-88-0238

## Summary

During the period of this grant, we completed several critical subsystems for the 1 GeV Linac and FEL Storage Ring, as well as performing necessary redesign on the Linac injector. The most noteworthy accomplishment was the design of a new undulator system for the Duke XUV FEL. This new undulator shows promise as an economical and effective source of coherent radiation tunable from the millimeter to the x-ray regions of the spectrum.

## Final Report, AFOSR-88-0238

Research Objectives: The following research objectives were proposed under this grant:

(1) Prepare the mechanical and shielding systems of the 1 GeV storage ring,

(2) Prepare a test section of the undulator required for UV/XUV FEL operation on the 1 GeV ring,

(3) Provide summer training opportunities for service academy cadets.

Progress: We made significant progress toward realizing the research objectives. In particular, we completed the modulators enabling us to drive the RF sources for the 1 GeV linac. We also made substantial progress on the mechanical and vacuum systems for the storage ring, to include completing the arc vacuum chambers. We completed both physics and engineering design studies on a more effective injector for the linac. We requested and received permission to perform preliminary work on the shielding for the MKIII FEL, a critical testbed for the UV/XUV FEL. This preliminary work was completed successfully.

Finally, we performed initial design studies for a completely new undulator design which offers promise to revolutionize the capabilities of the storage ring FEL, broadening its tuning range so that it will be an effective source from the millimeter wave to x-ray regions of the spectrum. These design studies have continued after the closing date of the grant and are summarized in a technical note, "Use of a Modular Undulator for the Production of Intense Coherent, Quasi-Coherent, and Inverse-Compton Radiation," attached as Appendix 1 to this report.

While we were unable to offer training to service academy cadets during the grant period, Major James Althouse, US Army, participated in an extremely important project concerning detecting and controlling electron pulses in the Linac.

Participating Professionals:

John M.J. Madey, Ph.D., Professor, Principal Investigator
Stephen V. Benson, Ph.D., Assistant Professor
David A. Kopf, Ph.D., Senior Research Scientist
Rodney I. McCormick, Ph.D., Associate Director
Nelson Hower, Chief Engineer
Chad McKee, Graduate Student
Bentley Burnham, Graduate Student
Brett Hooper, Graduate Student
Genevieve Barnette, Graduate Student
Wu-Shain Fann, Graduate Student
James Althouse, Graduate Student

## Final Report, AFOSR-88-0238

Advanced Degrees Awarded:

| | | | |
|---|---|---|---|
| Dec 1989 | James M. Althouse | M.A. (Duke) | No Thesis |
| Aug 90 | Wu-Shain Fann | Ph.D. (Stanford) | "Applications of Infrared Free Electron Laser in Nonlinear and Time Resolved Spectroscopy" |

Coupling Activities:

The following presentations were made at the 11th International Conference on Free Electron Lasers, August 28 - September 1, 1989, Naples Florida:

*Status of FEL Technology*, J.M.J. Madey
*A Synopsis of Research at the Duke FEL Laboratory*, S.V. Benson, J.M.J. Madey and R.I. McCormick
*Mode Control on Short Pulse FELs Using a Michelson-Mirror Resonator*, E.B. Szarmes, S.V. Benson and J.M.J. Madey
*A Demonstration of Loss Modulation and Cavity Dumping in a Free Electron Laser Oscillator*, S.V. Benson, et.al.
*Applications of Harmonic Generation of Picosecond Pulses From a Free Electron Laser*, B.A. Hooper et. al.
*Computer Simulation of Cathode Heating by Back Bombardment in the Microwave Electron Gun*, C.B. McKee and J.M.J. Madey
*First Demonstration of a Free Electron Laser Driven by Electrons From a Laser Irradiated Photocathode*, M.Curtin et.al.
*Applications of Infrared FEL in Picosecond and Nonlinear Optical Spectroscopies*, W.S. Fann et.al.

In addition, strong coupling activities in the form of briefings, visits, studies and workshops were carried out with the Electronic Devices and Technology Laboratory, Ft. Monmouth, NJ; the Strategic Defense Command, Huntsville, Alabama; the Strategic Defense Initiative Office (both Directed Energy and Technology Applications divisions), Washington, DC; and the Los Alamos National Laboratory.

New Discoveries: Although no patents or inventions were disclosed under this grant, the new undulator concepts outlined in Appendix 1 are very important and constitute an important contribution to the technology of short-wavelength FEL and synchrotron radiation light sources.

Conclusion: Substantial progress was made toward the overall goal of an UV/XUV radiation source and center during the period of this grant. In particular, we reported progress on linac and storage ring systems, injector redesign, and the design of a new undulator. Approximately six graduate students were in training during the period with two of those students receiving degrees. One of the degree recipients was an Army

major who is now a program manager at Headquarters, Strategic Defense Command, while the other illustrated the strong industrial interconnectivity of the program by performing part of his dissertation research in conjunction with scientists at Bell Communications Research. Coupling activities included extensive conference activity as well as substantial interaction with DOD and National Laboratories.

**Use of a Modular Undulator for the Production of Intense Coherent, Quasi-Coherent, and Inverse-Compton Radiation**

Duke FEL Laboratory Technical Note
March 1990

S. Benson, B. Burnham,
C. McKee and J. Madey

The 27 meter straight section on the Duke 1 GeV FEL ring provides an opportunity to develop a broad range of intense coherent, quasi-coherent, and incoherent tuneable light sources operating at wavelengths from 3000 microns to 0.3 Angstroms. Moreover, it appears possible to realize these light sources using a single multipurpose undulator and vacuum chamber; only the optics required for feedback, outcoupling, and the differing research applications of this system would have to be changed to change the operating wavelength and mode of operation.

The concept upon which this system is based is shown schematically in Figure 1. Although iron core electromagnets cannot produce as strong magnetic fields in short-period undulators as pure or hybrid REC permanent magnets, the sign and magnitude of the field generated by electromagnets can be controlled by changing the sign and magnitude of the current. Furthermore, the field can be tapered as necessary. Hence, if the undulator is constructed as shown in Figure 1 using a series of small, high field electromagnets which excite at most two or three adjacent poles, the period, sign, and magnitude of the magnetic field in the undulator can be modified by varying the excitation of the individual electromagnets.

The configurations of interest in such a system are shown schematically in Figure 2. If the adjacent poles of the undulator have the opposite excitation and the magnitude of the excitation is uniform along the length of the undulator, a "short-period" untapered undulating field is formed as shown in Figure 2A. Although the field strength of the undulator will be limited by pole tip saturation and the exponential decay of the field in the gap between the poles, sufficient field should be available to produce intense quasi-coherent spontaneous radiation in the soft X-ray region.

Alternatively, the immediately adjacent poles can be excited with the same polarity, switching to the opposite polarity in the next set of poles as shown in Figure 2B. In this

configuration, an undulating field is formed with a period two or three times the period of the short-period undulator. The magnetic field in this case will also be higher due to the reduced leakage flux between poles and the greater period. Assuming operation of the short-period undulator at 50 Angstroms, this second configuration could in principle be operated at wavelengths as short as 200-300 Angstroms (at low $K^2$) depending on the number of poles excited by a single electromagnet.

Finally, a larger block of poles could be excited to produce a very long period undulator as shown in Figure 2C. There is in principle no limit to the period which could be obtained in this configuration, although the transverse dimensions of the vacuum chamber would set a practical limit to the useable value of K. To limit the transverse excursion of the electron beam, it is probable that the undulator would be excited to generate the "square-wave" electron orbit shown in the figure rather than the sinusoidal orbits appropriate for low and medium-K undulators. This orbit maximizes the phase shift per unit length of the undulator for a given horizontal excursion and minimizes the heat load on the downstream optics.

In addition to the variation of period, this concept also permits the variation of the field strength along the undulator as required for operation of "bucket-deceleration" or "phase-displacements" FEL amplifiers or oscillators. As discussed further below, operation of a portion of the 50 Angstrom undulator as a phase displacement amplifier appears to offer the possibility of substantially higher peak and average power output as compared to operation as a pure spontaneous radiator.

Finally, it is possible to excite "blocks" of poles along such an undulator to form one or more dispersive sections as required for operation of an optical klystron. When distributed along the length of a long undulator, such dispersive sections offer both the possibility of enhanced small signal gain and a reduced optical power threshold for entry into the large signal regime (Figure 2D).

In addition to the control of undulator configuration, the independent excitation of the poles of the undulator as shown in Figure 1 should permit the correction of the electrons' trajectories through the undulator on a pole by pole basis under computer control as determined either by bench tests of the individual electromagnet assemblies prior to assembly or by measurements of the transverse position of the electron beam along the undulator.

Assuming a 20 mm gap between poles, it appears possible using water cooled copper coils rated at 1000 amps/cm$^2$ and supermendur poles to operate such an undulator with a pole spacing of

14 millimeters (corresponding to a period of 28 mm) and a K-value, in the short-period configuration shown in Figure 2A, of 0.6. Such an undulator could be magnetically tuned to cover the 40-50 Angstrom wavelength range as a spontaneous radiator or phase displacement amplifier, and could also be used for the planned high gain UV and XUV amplifier and oscillator experiments as well as a long period undulator for a mm-wave isochronous FEL/inverse Compton scattering source.

The configurations of the soft X-ray, UV/XUV, mm-wave and hard X-ray sources which can be realized using such an undulator are shown in Figures 3 and 4. The soft X-ray spontaneous radiation source shown in Figure 3A is the simplest of the possible devices, consisting only of the long, short period undulator and the undulator vacuum chamber. Computations indicate that at 50 Angstroms more than 100 watts peak power would be emitted by this source into the $TEM_{00}$ mode assuming a peak current of 270 Amps at 1 GeV. The average power radiated by this quasi-coherent source into the $TEM_{00}$ mode would be 27 milliwatts. The coherence length, whose limit is determined by the energy spread of the electron beam, would be 4 microns.

By modifying the second half of the undulator as shown in Figure 3B to serve as a phase-displacement amplifier[1], and using the first half of the undulator as a spontaneous radiator to generate the optical electric field required to create the "empty buckets" which are accelerated upwards through the electron beam in the amplifier, it appears possible given the beam energy and current of the FEL ring to achieve a power gain of 1000 in the amplifier and an instantaneous peak power output in excess of 100 kilowatts. In addition to the promise of improved peak power output, the "empty buckets" used to displace the electrons during amplification do not, in theory, perturb the energy spread or emittance of the circulating electron beam. To the extent that this result is realized in practice, high cw power output may also be available in the soft x-ray region from this system.

The resonator mirrors shown in Figure 3B serve to stabilize the amplitude and phase coherence of the optical field at the input to the phase displacement amplifier following startup. However, the reflectivity of these mirrors need not be high given the anticipated gain of the amplifier. Useful power output should be possible even without a resonator should mirrors be unavailable.

As noted above, a medium-period, medium $K^2$ undulator can be formed by exciting the poles as shown in Figure 2B. The operation of such an undulator using the circulating electron beam in the FEL ring for amplifier and oscillator experiments in the ultraviolet and extreme ultraviolet as shown in Figure 3C has previously been described in the literature[2]. For operation as

a light source, a resonator is required to supply feedback around the FEL interaction region. While such a system is believed capable of high peak power output and relatively high gains should be available, particularly at wavelengths longer than 500 Angstroms, mirror reflectances in excess of 50% will be required for oscillator operation at 200 Angstroms. As the availability and lifetime of such mirrors remains uncertain, the short wavelength operating limit of such systems remains somewhat uncertain. The undulator configuration shown in Figure 2B (period = 11.2 cm) should permit operation of this light source at wavelengths as short as 500 Angstroms using the Duke ring.

Use of the long-period variant of the undulator for operation of an isochronous mm-wave FEL oscillator is shown schematically in Figure 4A. The special requirements and operating characteristics of isochronous free electron lasers have been analyzed by Deacon[3]. In such a device, the optical buckets created during the interaction of the electrons and the amplified optical radiation during passage through the interaction region are preserved during the electrons passage through the arcs and RF cavity of the ring. The electrons energy spread and emittance are thus unaffected by the interaction, permitting operation at high average power output.

To attain operation in this mode, the transit time of the electrons through the arcs of the ring must be substantially independent of energy, thus the use of the term "isochronous" to describe such systems. As the degree of isochronicity required depends on the wavelength, it is easier to operate such systems at longer wavelengths. The momentum compaction factor required for operation at 1 mm, alpha=0.002, appears achievable[4]; the prospects for operation at shorter wavelengths are unknown.

The power output of isochronous FELs is limited by the RF power available to reaccelerate the circulating electrons, by RF or optical heating and/or breakdown, and by the magnitude and nonlinearity of the momentum compaction factor. Of these factors, the heating of the waveguide enclosing the interaction region, which must also serve as the vacuum chamber for the undulator, will likely be the limiting factor. While an average power in excess of 10 kilowatts at 1 mm should be possible given the RF power installed on the Duke ring, the limit imposed by vacuum chamber heating is probably closer to a kilowatt. In either case, the available peak power would be higher by a factor of $10^3$-$10^4$ given the length and spacing of the circulating electron bunches.

A resonator is also required for the isochronous FEL to provide sufficient optical power at the entrance to the undulator to re-form and maintain the optical buckets which trap the electrons. Figure 4A shows a schematic of a quasi-optical resonator in which the radiation emerging from a horn at the end of the waveguide/vacuum chamber is reflected from a spherical mirror and re-

injected into the waveguide. Such quasi-optical techniques will be necessary to permit the injection and extraction of the electron beam from the undulator.

Given its high peak power capability, such a system is of potential interest for research requiring a tuneable mm-wave power source. It is also of interest as a driver for production of X-rays in the 3-30 keV region by Compton back-scattering as shown schematically in Figure 4B. As shown in the Figure, the intense, picosecond mm-wave pulse generated by the source is focussed to a waist with Rayleigh range equal, approximately, to the electron bunch length, using a mirror downstream from the undulator. When correctly timed, the electron bunch passes through the waist of the counter-propagating optical pulse encountering an intense, focussed mm-wave field. The probability for emission of a back-scattered Compton photon is high in this geometry due to the high energy density in the propagating optical pulse.

The system shown in Figure 4B is of interest since, for initial photon wavelengths between 300 and 3000 microns, the backscattered photons appear as hard X-Ray quanta with energies between 3 and 30 keV assuming 1 GeV electron energy. As compared to the X-radiation generated by wiggler sources, the bandwidth of the scattered quanta is determined (for a collimated X-ray beam) by the bandwidth of the initial mm-wave wavepacket. Thus, it is possible that the scattered quanta could be used directly for some spectroscopic and imaging applications without the use of a monochromator. Finally, the scaling laws for Compton scattering do not impose a short-wavelength spectral cutoff. As compared to a high field wiggler, in which the the short wavelength limit is determined by the electron energy and magnetic field, it appears that inverse Compton X-ray sources should have intrinsically superior output in the hard X-ray region at photon energies greater than 10 keV.

As is apparent from Figures 3 and 4, while a common electromagnetic undulator and vacuum chamber can be configured to operate as a light source at wavelengths from thousands of microns to tenths of Angstroms, the optics required for operation in these regions will differ. Hence, the actual flexibility of the proposed source will depend on the extent to which the optical systems for these sources can be exchanged. The situation is clearly the most critical for the sources requiring precisely aligned resonator mirrors which must, due to timing considerations, be placed in overlapping regions along the optical axis. However, even in the worst case, it should always be possible to switch rapidly between any one of these sources and the operation of one of the quasi-coherent spontaneous sources through the use of a flip-in turning flat on the optical axis to extract the spontaneous power (Figure 4C).

The estimated peak power output and brightness for these sources for the Duke 1 GeV ring and the assumed undulator parameters (14 mm pole spacing and 3.3 kilogauss on-axis field ) are shown in Figures 5 and 6.

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1 N. M. Kroll, P. L. Morton, and M. N. Rosenbluth, IEEE J. Quant. Elect. QE-17, (1981) 1436.

2 J. E. LaSala, D. A. G. Deacon, and J. M. J. Madey, Nucl. Inst. Meth, Physc. A250 (1986) 262.

3 D. A. G. Deacon, Phys. Reports 76 (1981) 349.

4 D. A. G. Deacon, Theory of the Isochronous Storage Ring Laser, Ph.D. Thesis, Stanford University (1979).

## Figure Captions

1.) Schematic of proposed modular undulator. Each Vanadium supermendur yoke drives three undulator poles with the same polarity. The field of each yoke can be reversed.

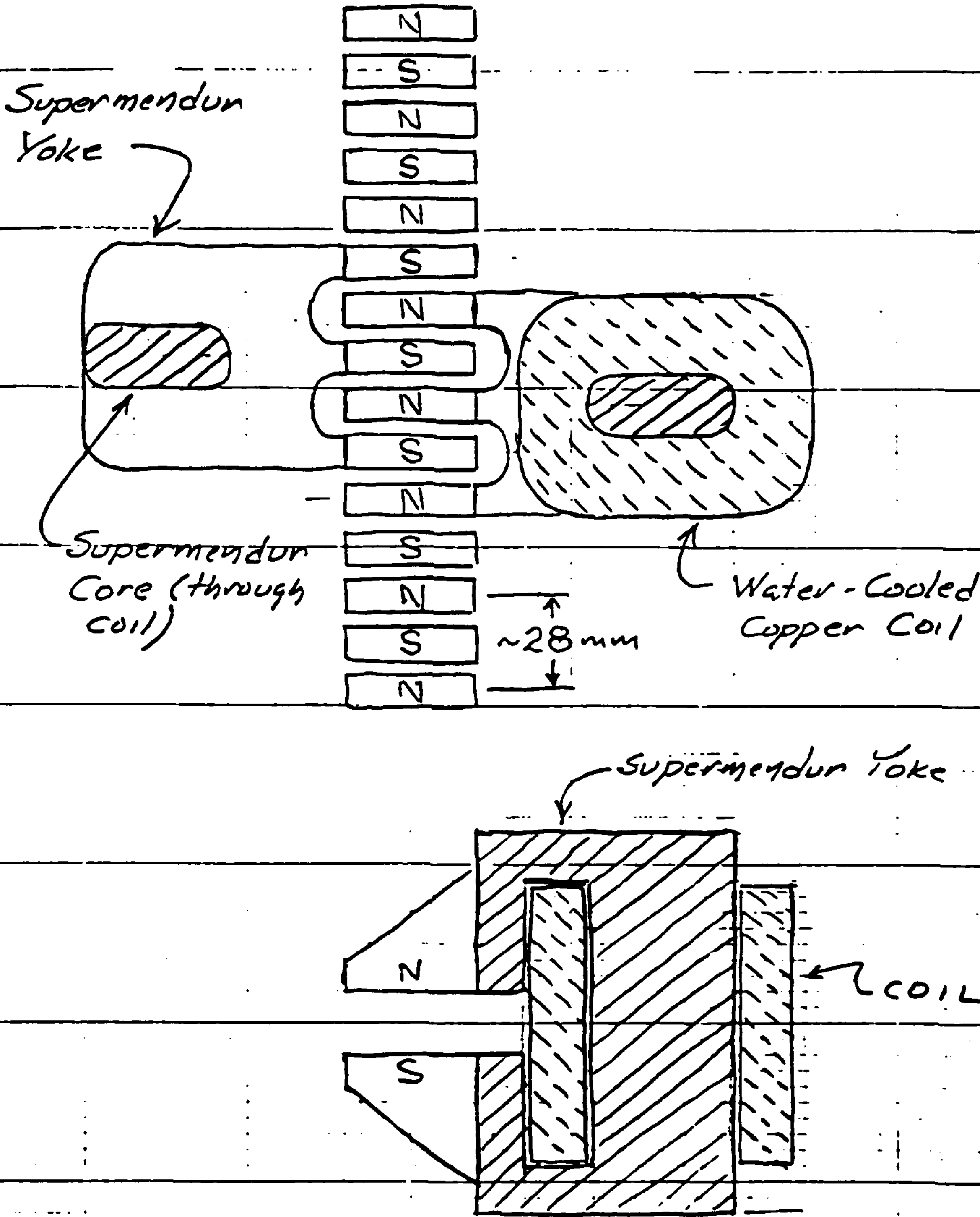
2.) Four possible configurations of the modular undulator. a.) Each pole different in polarity from the next to form a short period undulator. b.) Undulator yokes reversed in order to increase the undulator period by a factor of three or four and produce a longer period, high K wiggler. c.) Field required to produce a square wave trajectory to maximize the phase slip per period for a given transverse motion. d.) Distributed optical klystron with the periods of some of the magnets reversed to produce a dispersive section.

3.) Three possible laser configurations possible with the modular undulator. a.) Quasi coherent source from short period undulator. b.) Soft X-ray laser produced by using a phase displacement amplifier with a soft X-ray spontaneous driver. The resonator need not be low loss in this case. c.) UV/XUV laser produced with medium period undulator and a stable resonator. Losses must be kept rather low in this design.

4.) Compton backscattering source. a.) Isochronous storage ring millimeter wave laser with quasi optical cavity. b.) Compton backscattering interaction region. The electron and optical beams are both focussed down to a tight waist to maximize the interaction.

5.) Peak power output of FEL sources at Duke vs. other coherent sources. The peak power of both the spontaneous radiator and the phase displacement amplifier is given at 50 Å.

6.) Brightness of Compton backscattering source vs. the best existing wiggler sources. Note that the existing sources are on the much higher energy X-ray ring at Brookhaven.


N
S
Supermendur
Yoke
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Copper Coil
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Supermendur Yoke
N
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COIL

FIGURE 1

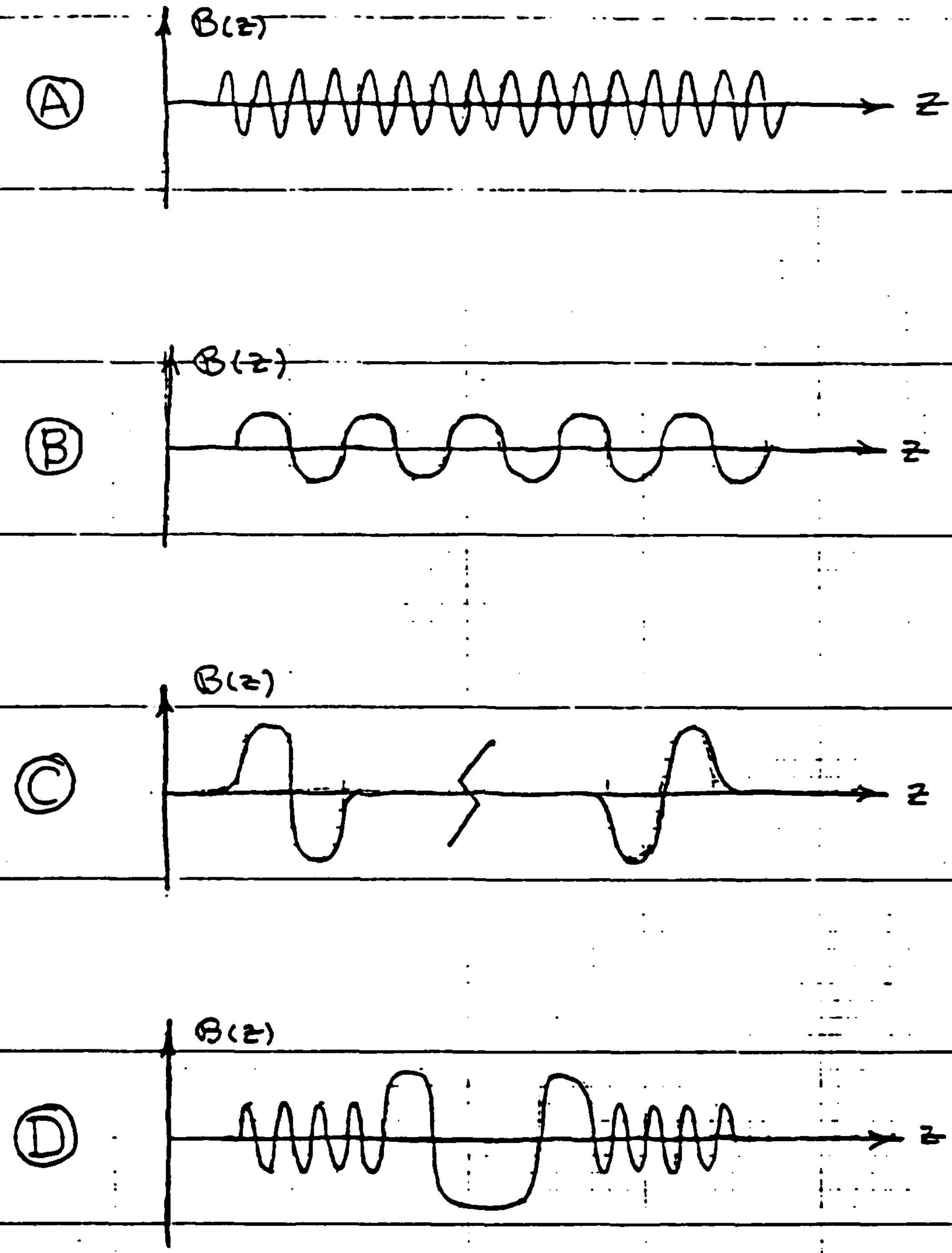



FIGURE 2

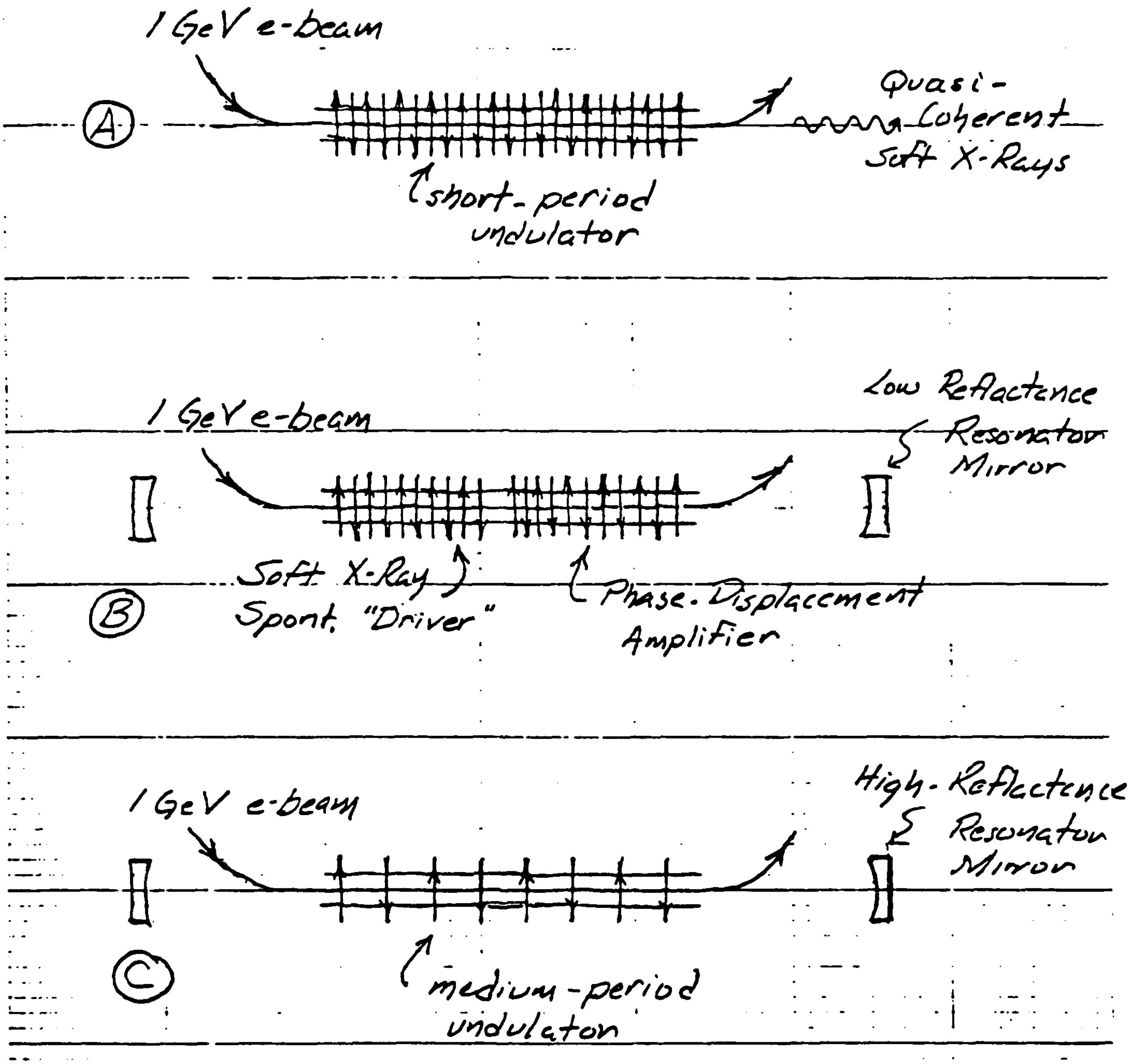

1 GeV e-beam
Quasi-Coherent Soft X-Rays
A
short-period undulator
1 GeV e-beam
Low Reflectance Resonator Mirror
Soft X-Ray Spont. "Driver"
Phase-Displacement Amplifier
B
1 GeV e-beam
High-Reflectance Resonator Mirror
C
medium-period undulator

FIGURE 3

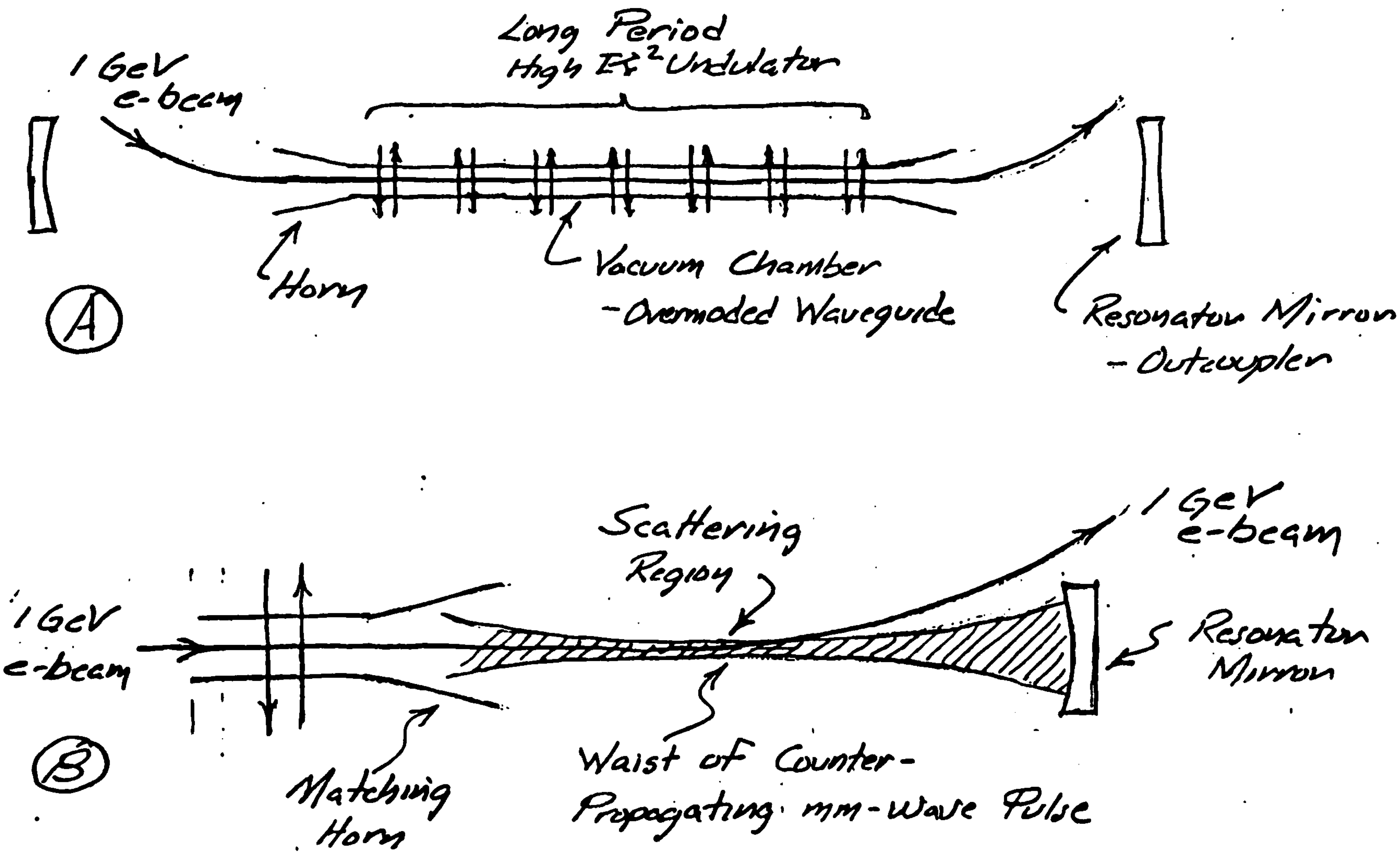
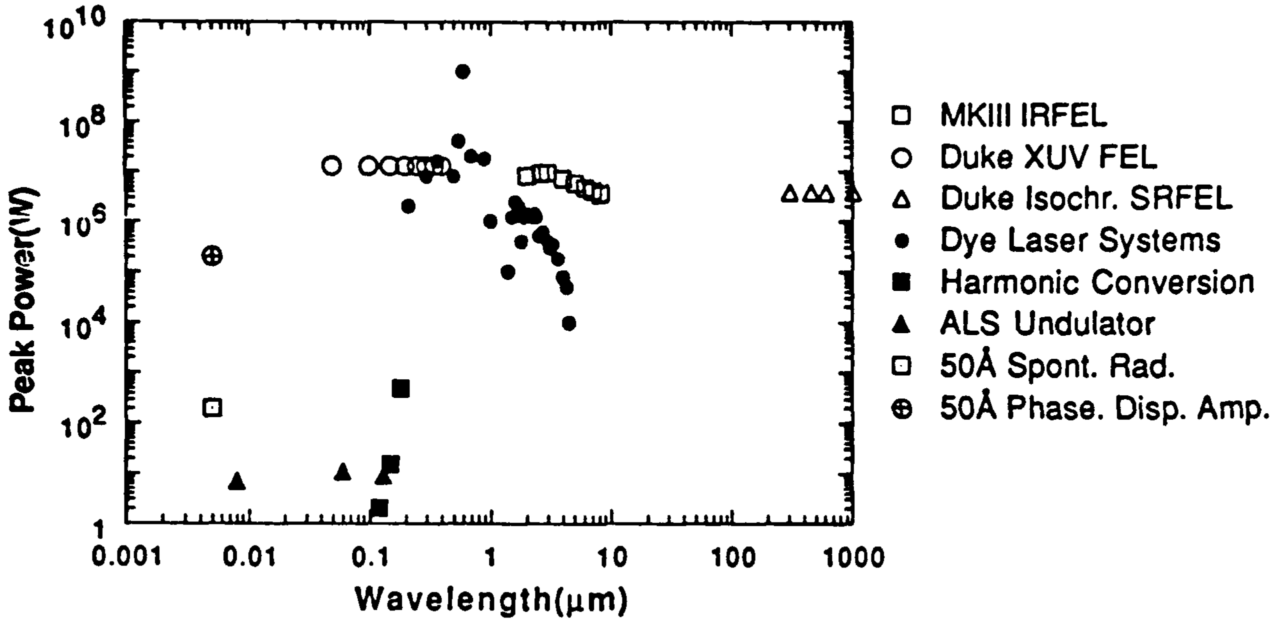

Long Period
High $E\lambda^2$ Undulator
1 GeV e-beam
Horn
Vacuum Chamber
-Overmoded Waveguide
Resonator Mirror
- Outcoupler
A
Scattering Region
1 GeV e-beam
1 GeV e-beam
Resonator Mirror
Matching Horn
Waist of Counter-Propagating mm-Wave Pulse
B

FIGURE 4

## Figure 5




## Figure 6